Non-contact Thermophysical Characterization of Solids and Fluids for Gen3 Concentrating Solar Power

Generation 3 Concentrating Solar Power Systems
FOA: DE-FOA-0001697
Topic Area 2B - Gen3 Research and Analysis

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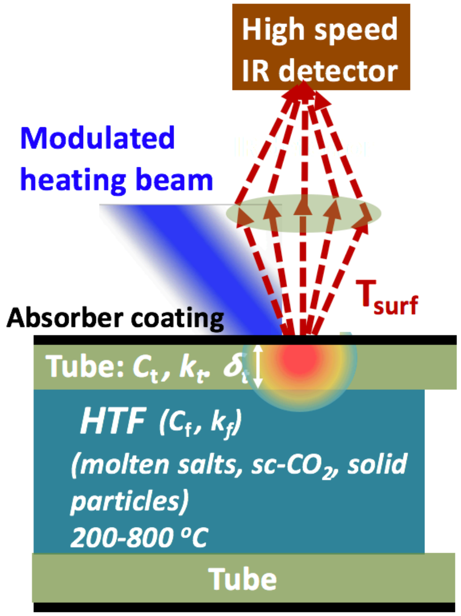
Objectives and Impacts

- **Problem Statement**
  - Challenging and time consuming to measure thermophysical properties of high-temperature HTFs, e.g., particles and molten salts
  - Lack of *in-situ* diagnostic tools to monitor thermophysical properties of HTFs
- **Objectives**
  - Develop a technique based on "*modulated photothermal radiometry*" or "***MPR***", to measure thermal conductivity (*k*) and specific heat (*C*) of heat transfer fluids (HTFs), solar receiver tubes, coatings, up to 800^{o}C
  - Aim for **accurate**, **fast**, **non-contact** measurement of **both *k* and *C***.
  - Use the tool for *in-situ* diagnostics *of* materials in CSP plants and of their corrosion behaviors.
- **Impacts to Gen3 CSP**
  - Facile and room-to-high temperature thermophysical measurements of emerging solids (e.g., particles) and fluids (e.g., molten salts) for Gen3 CSP systems.
  - Transition of the diagnostics tool for laboratory and *in-situ* testing in other Gen3 projects.

Working Principles of MPR

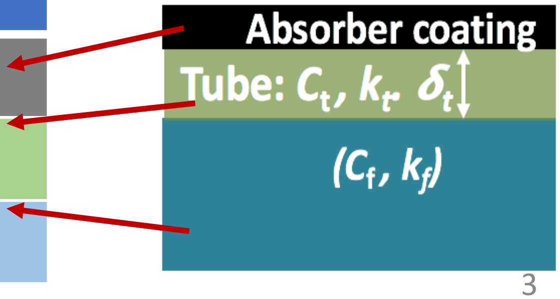
Key Principles and Merits

- By changing the modulation frequency and the thermal penetration depth of the heating beam, the surface temperature will be sensitive to *k* and *C* of different layers (HTF, tube, and coating).
- Lock-in technique for surface IR thermometry with high resolution.
- Works for both rough and smooth surfaces, as well as particles.
- Suitable for high temperature measurements (IR emission is stronger at higher temperature)
- Non-contact (good for corrosive media), rapid (minimal sample preparation), low-cost



Thermal penetration depth: $L_p = \sqrt{2\,\alpha/\omega}$

Frequency (Hz)	Penetration depth (mm)
>60 kHz	0.01-0.1
10-100	0.1-1
0.1-10	1-10

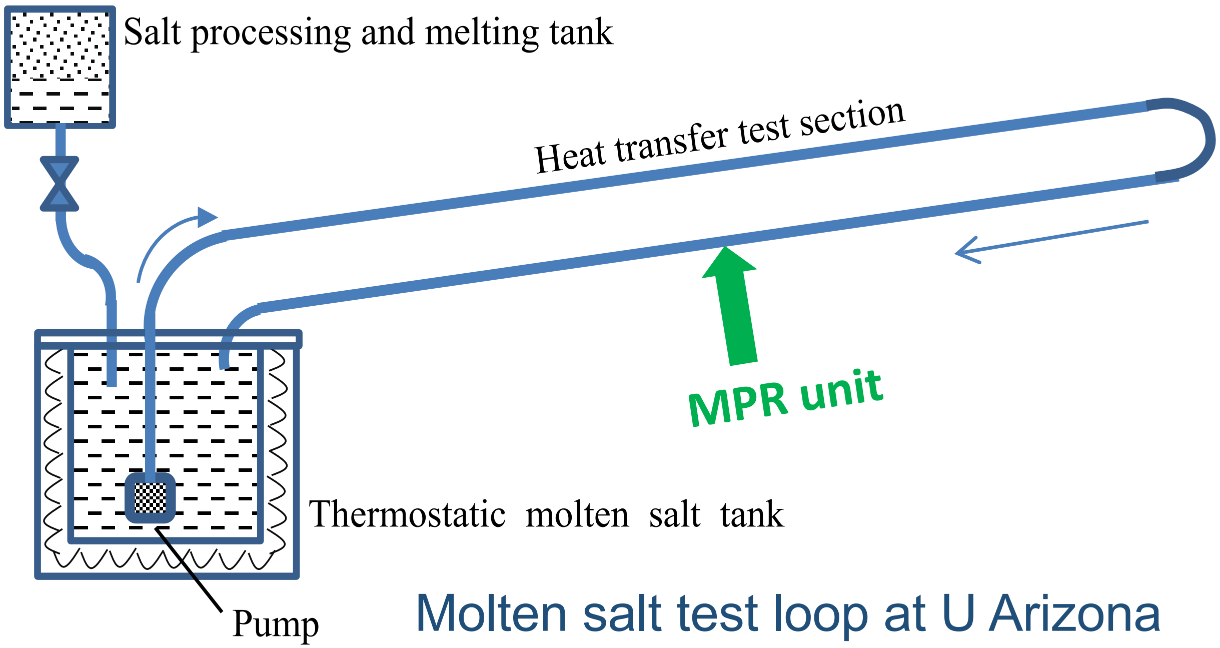


MPR can also measure flowing fluids and falling particles

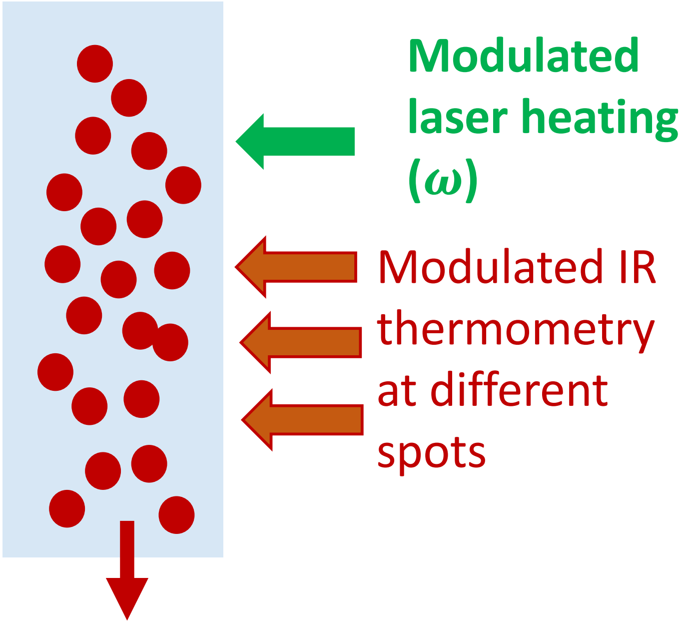
- Governing equation (no viscous dissipation): $\alpha \nabla^2 T = \frac{\partial T}{\partial t} + \boldsymbol{\vec{v}} \cdot \boldsymbol{\nabla T}$
- With the known velocity field $\vec{v}$, the equation can be exactly solved.
- We will test this idea on a molten salt test loop (U Arizona) and also on falling particles

Molten salt

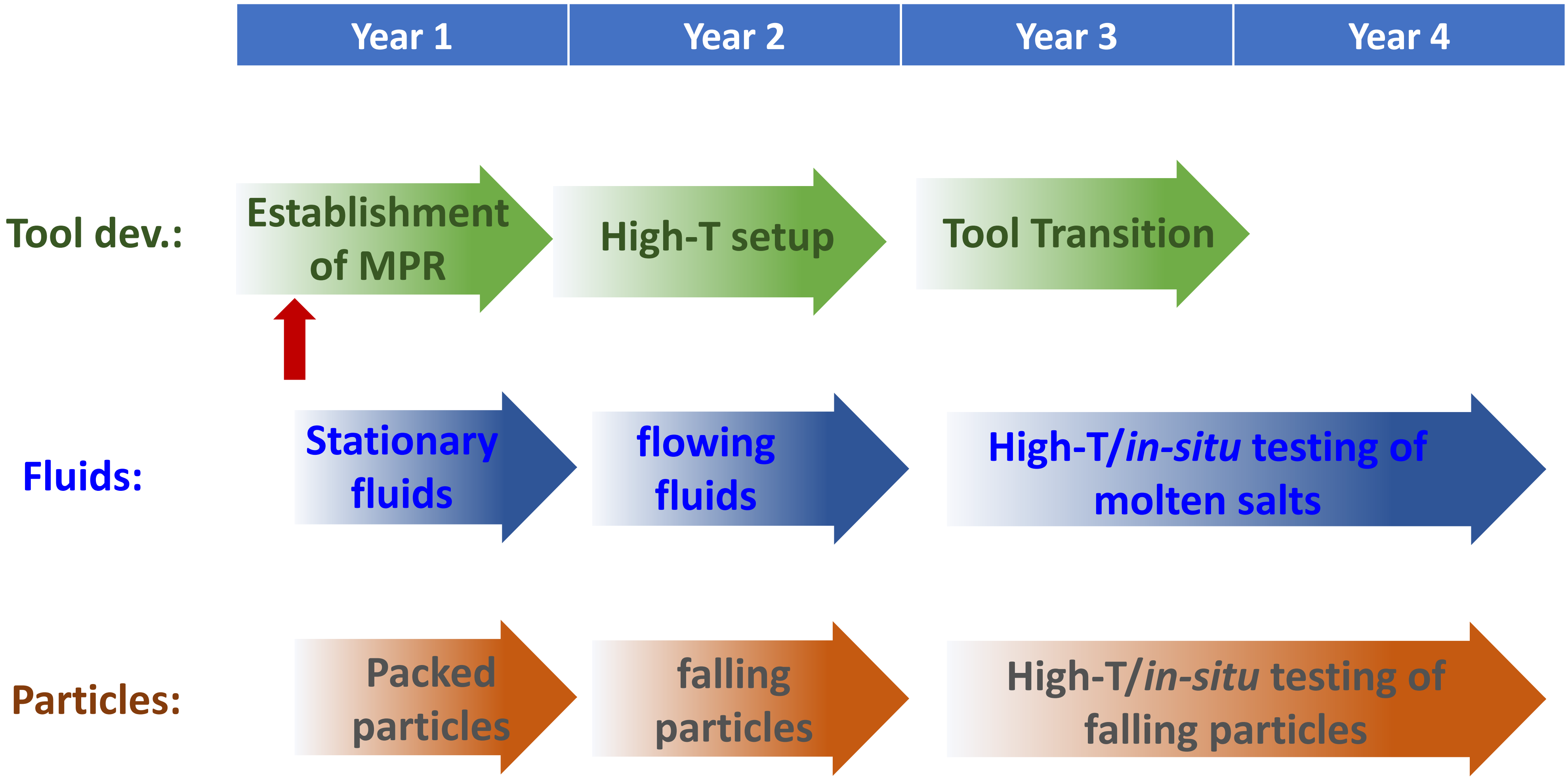
Falling particles



Molten salt test loop at U Arizona



Work Plan and Milestones



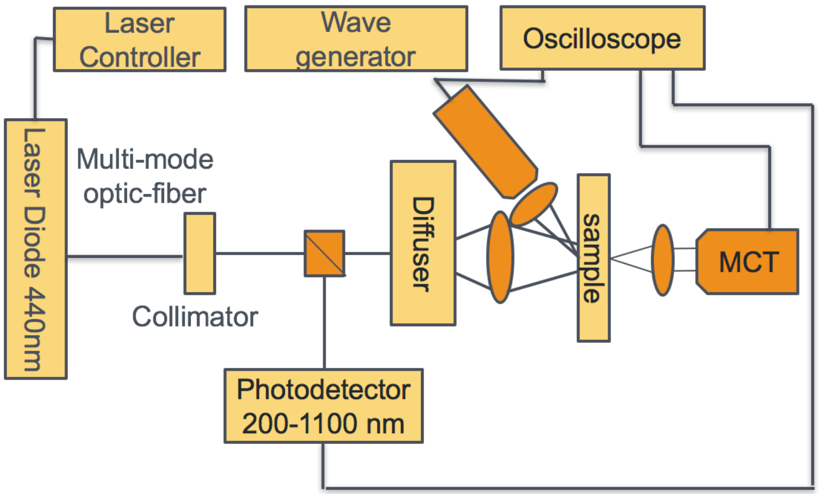
Year 1 | Year 2 | Year 3 | Year 4

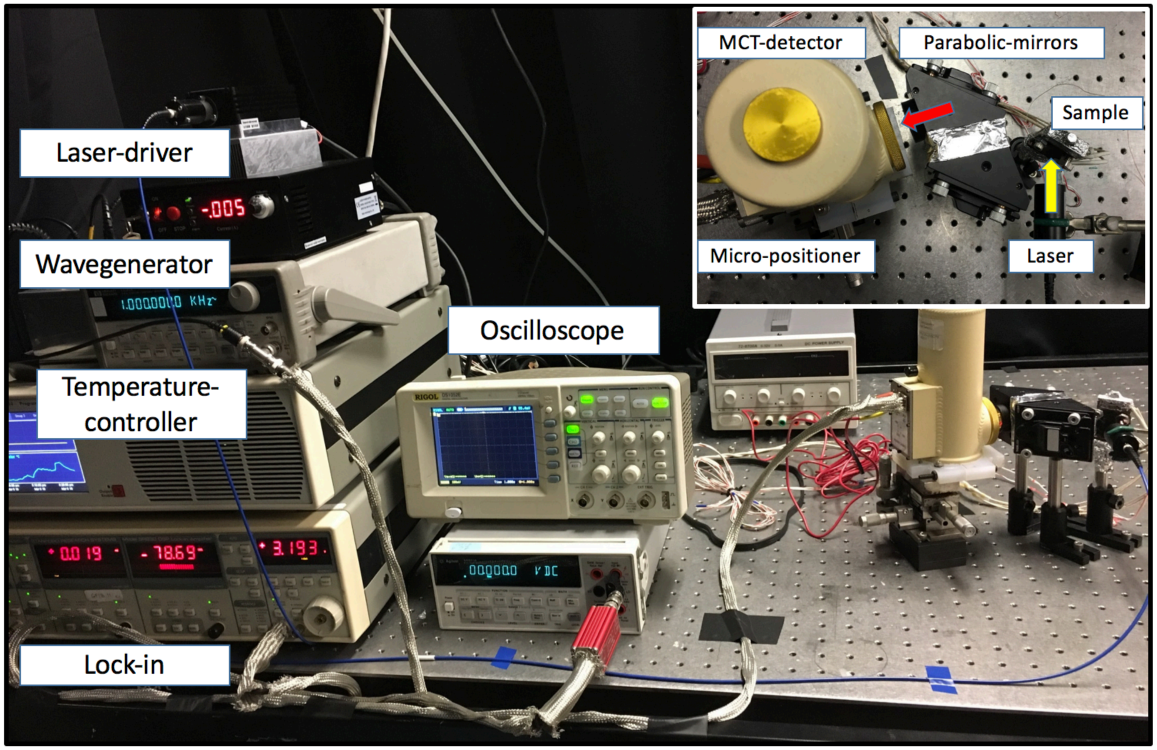
Tool dev.:
- Establishment of MPR
- High-T setup
- Tool Transition

Fluids:
- Stationary fluids
- flowing fluids
- High-T/*in-situ* testing of molten salts

Particles:
- Packed particles
- falling particles
- High-T/*in-situ* testing of falling particles

MPR Setup at UCSD





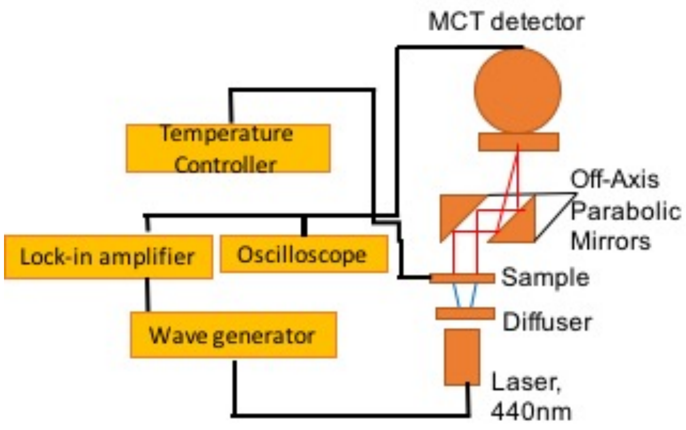
MCT detector

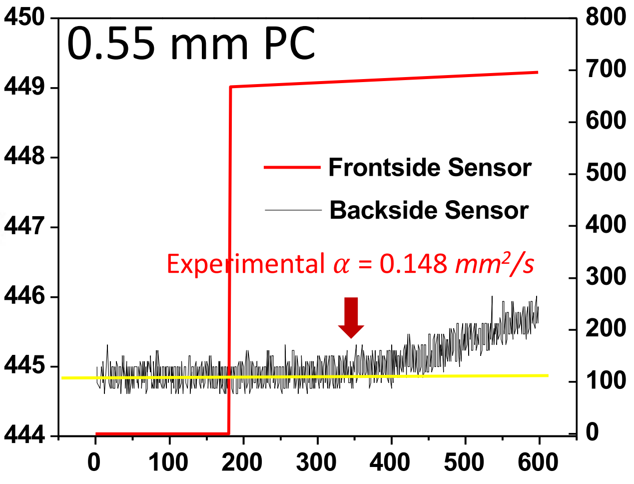
Pyrometer

	MCT Detector	Pyrometer
Model	KMPV11-1-J1 HgCdTe (MCT)	MPAC, IGA 320/23-LO
Detc.Size (mm)	0.25	0.2
cut-off λ (μm)	2.0-12.0	2.0-2.60
Resp. Time (sec)	1.86×10^{-7}	2×10^{-3}

Front-side heating, back-side thermometry to yield thermal diffusivity (similar to laser flash)

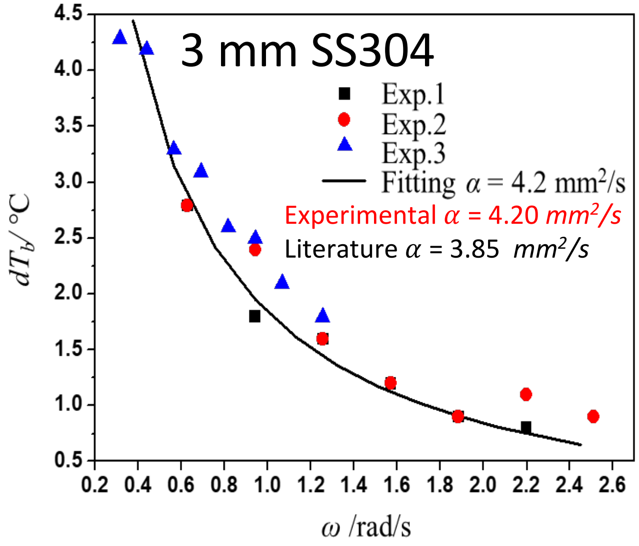
Time domain





$$\boxed{L = 12\sqrt{\alpha t}}$$

Frequency domain



Sample	Time delay (sec)	α_{exp} (mm^2/s)	α_{ref} (mm^2/s)
0.55 mm PC	0.170	0.149	0.144
5.4 mm POM	18	0.122	0.11
3 mm SS304	0.2	3.75	3.85
3.26mm Borosilicate glass	1.4	0.633	0.619

$$dT_b = \frac{q_s}{e}\sqrt{\frac{2}{\omega}}\exp\left(-L\sqrt{\frac{\omega}{2\alpha}}\right)$$

Front-side heating, front-side thermometry to yield both diffusivity & conductivity

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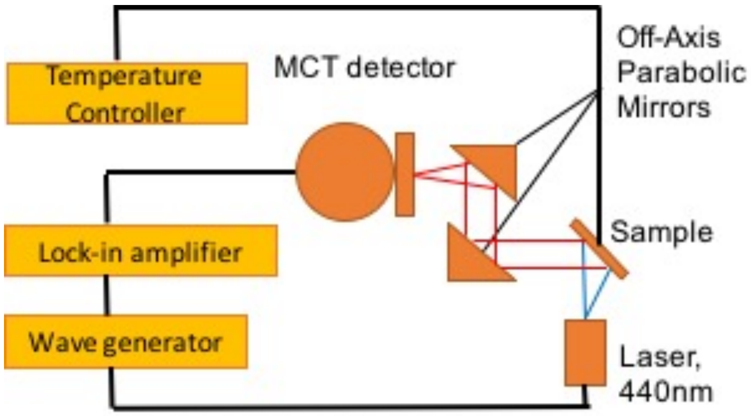
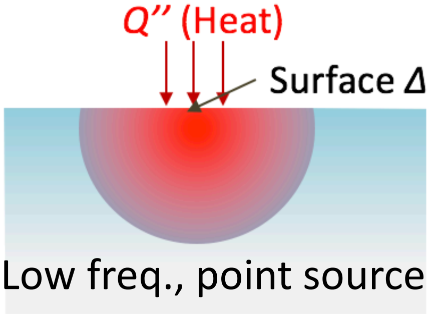
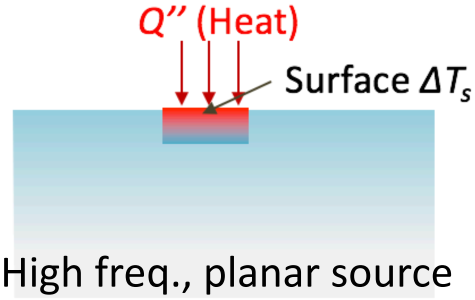


Sample	α_{exp} (mm^2/s)	α_{ref} (mm^2/s)	k_{exp} (W/m-K)	k_{ref} (W/m-K)
SS304	4.0	3.85	16.0	14.9
Glass	0.62	0.619	1.14	1.15

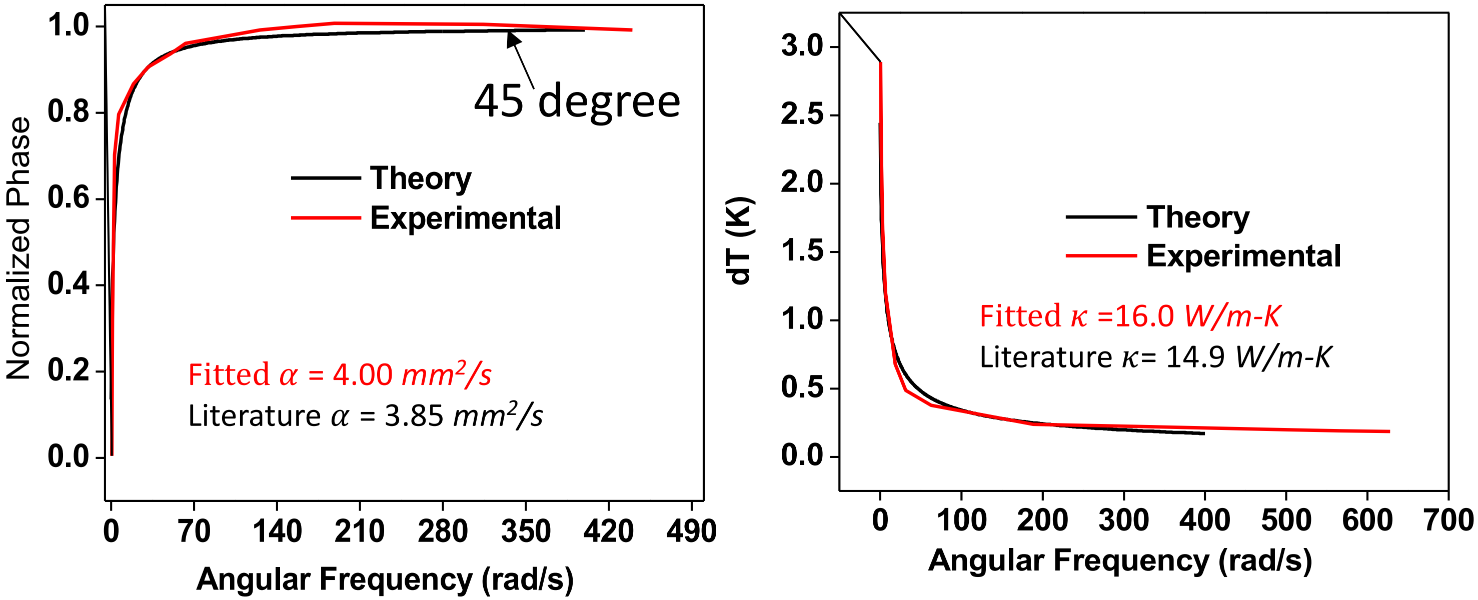


Low freq., point source



High freq., planar source

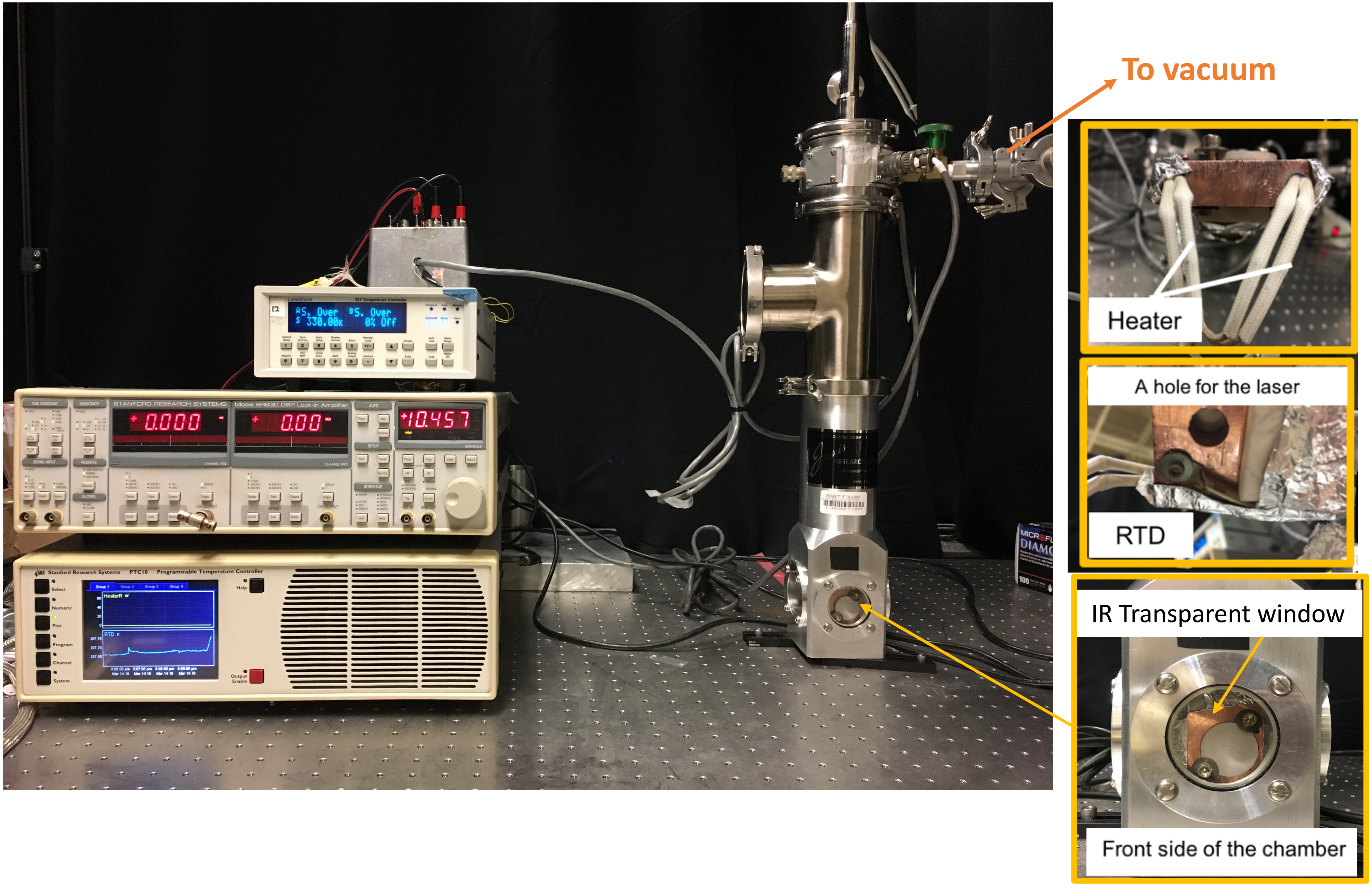
3 mm SS304



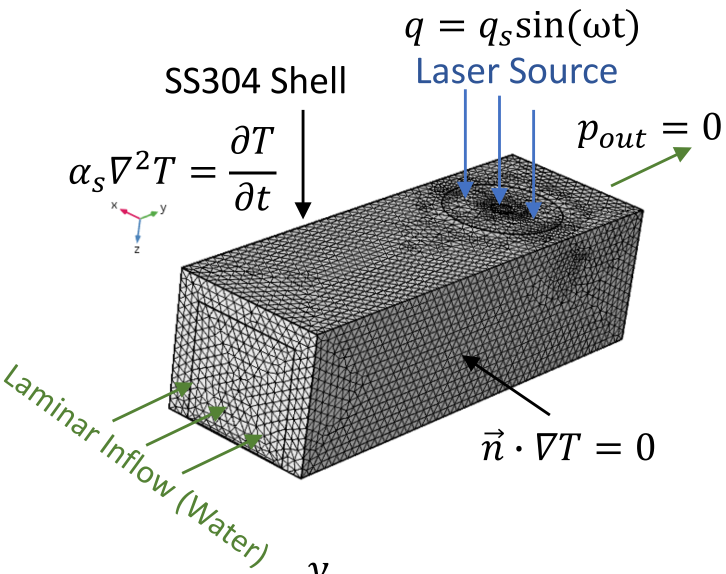
Front side temperature:

$$dT_f = 2\pi q_s \int_0^\infty G(k)\exp\left(\frac{-\pi^2 k^2 ({w_0}^2 + {w_1}^2)}{2}\right) k\,dk, \text{ where } G(k) = \frac{1}{k\sqrt{(4\pi^2 k^2 + i\frac{\omega}{\alpha})}}$$

Building high-temperature setup



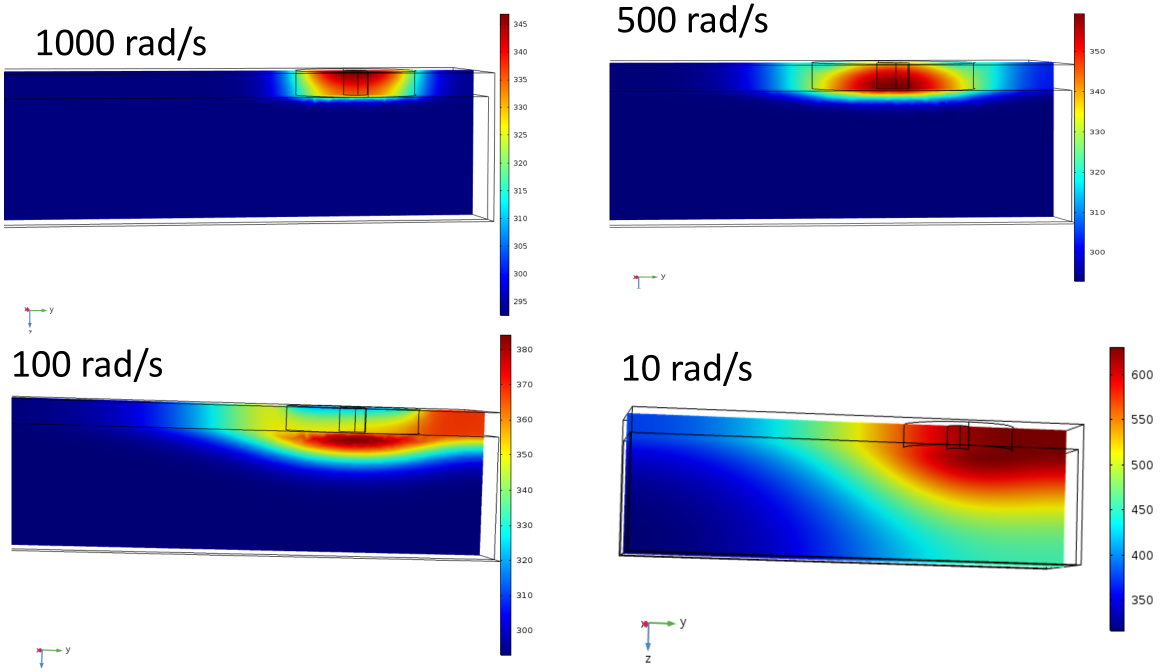
Designing particle and fluid setups



$$U(y) = U_{max}[1 - (\frac{y}{R})^2]$$

where U_{max} = 1 m/s

$$\alpha_l \nabla^2 T = \frac{\partial T}{\partial t} + \vec{v} \cdot \nabla T$$



COMSOL modelling of solid-liquid coupled heat transfer. (a) Simulation model. and (b) Snapshot of temperature contour at the center at around $T/2$. The penetration depth is greater than the wall thickness when $\omega < 100$ rad/s

Summary and work plan

- Established MPR setup around room temperature
  - Front-side heating, back-side thermometry to yield diffusivity (similar to LFA)
  - Front-side thermometry to simultaneously yield both diffusivity and conductivity
- Currently validating the measurements on a wide range of solid materials to determine systematic and random errors (YR 1)
- Build the high temperature setup (800^{o}C) (YRs 1-2)
- Measure packed particles and stationary fluids (YR 1)
- Design and implement MPR for flowing fluids and falling particles based on front-side thermometry (YRs 1-2)
- Establish high-temperature MPR setup for solids, flowing fluids, falling particles, and tool transition (YRs 3-4)

- Backup slides

1. Thermal Properties Measurement of Known Samples

1.1 LFA Measurement of PC

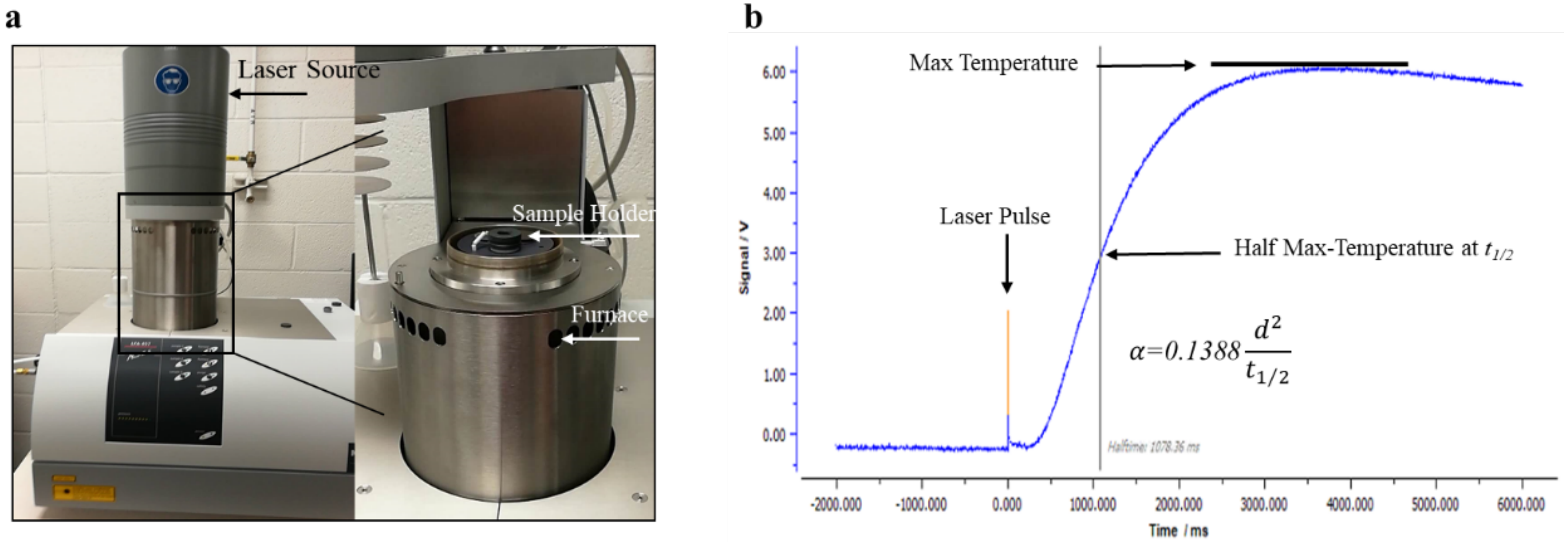


Fig.1. LFA measurement method for the PC with d = 1.1 mm (a) NETSCH LFA system; and
(b) Determination of α by recording the time for half the maximum temperature in the temperature-rise curve.

1. Thermal Properties Measurement of Known Samples

1.1 LFA Measurement of PC

Table.1. Summary of *α* and *κ* of PC at 25℃ with different thickness

Test	**Thickness = 1.1 mm**		**Thickness = 0.25 mm**	
	T / ℃	α / mm²/s	T / ℃	α / mm²/s
1	24.8	0.148	26	0.143
2	25.3	0.146	25.2	0.143
3	25.6	0.146	25	0.142
4	24.8	0.16	24.8	0.143
5	24.7	0.148	25.2	0.156
6	24.6	0.144	25.1	0.156
7	25.9	0.143	24.9	0.155
8	25.2	0.143	24.7	0.155
9	25.2	0.142	24.8	0.155
10	24.7	0.158	-	-
Average	25.1	0.148	25	0.151
STDEV	-	0.006	-	0.02
Calculated κ	0.212		0.217	

1. Thermal Properties Measurement of Known Samples

1.3 Measurement of Liquid and Powder using Hot Wire Method

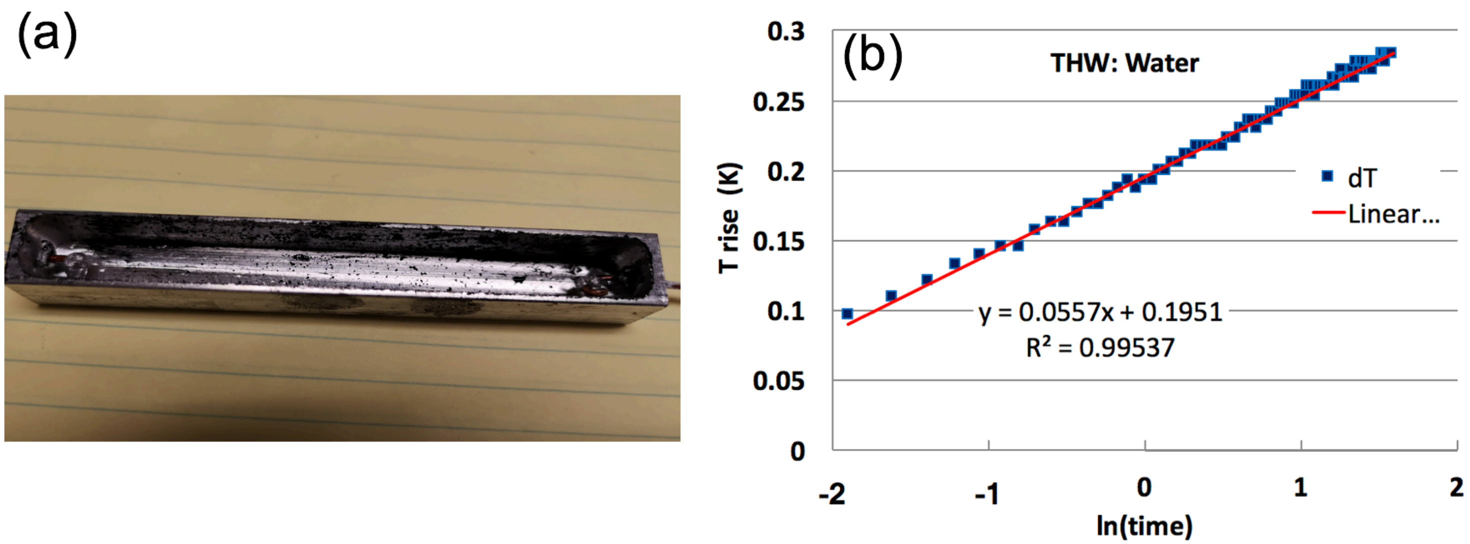


Fig. 4. Transient hot wire (THW) method.
(a) Photograph of the setup. (b) Recorded vs. ln(*t*) data for water at room temperature.

1. Thermal Properties Measurement of Known Samples

1.3 Measurement of Liquid and Powder using Hot Wire Method

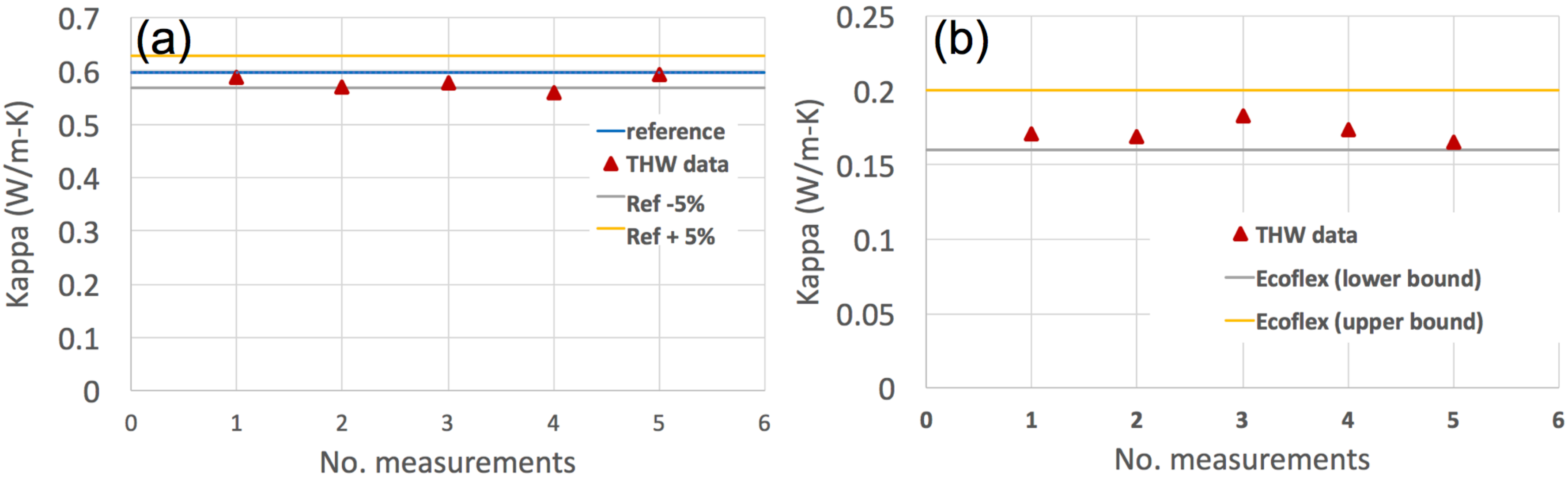
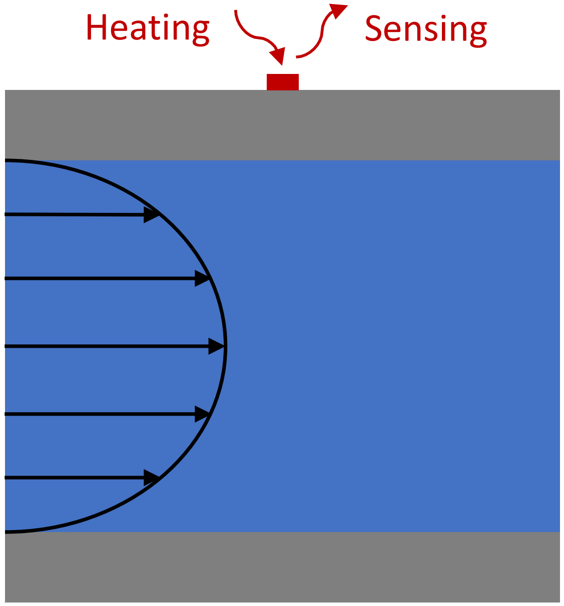


Fig. 5. Measured thermal conductivity from the THW method for (a) water and (b) Eco-flex.

8. Preliminary Analysis of Solid-fluid Coupled Measurement



Governing equation in the tube wall:

$$\alpha_s \nabla^2 T = \frac{\partial T}{\partial t}$$

Governing equation in the fluid:

$$\alpha_l \nabla^2 T = \frac{\partial T}{\partial t} + \vec{v} \cdot \nabla T$$

With known velocity field solid properties, numerical simulation can be used to fit experimental result and extract fluid thermal property

Laminar

$$U(y) = U_{max}[1 - (\frac{y}{R})^2]$$

Turbulent

$$u^+ = y^+, \qquad \text{when } y^+ < 5$$

$$u^+ = 5\ln y^+ - 3.05, \qquad \text{when } 5 < y^+ < 30$$

Where the dimensionless velocity and coordinate are:

$$u^+ = \frac{U}{\sqrt{\tau_w/\rho}}, \qquad y^+ = \frac{y}{\nu/\sqrt{\tau_w/\rho}}$$

$$\tau_w = f\rho U^2/8, \qquad f = 0.184 \mathrm{Re}_D{}^{-0.2}$$

Designing particle and fluid setups

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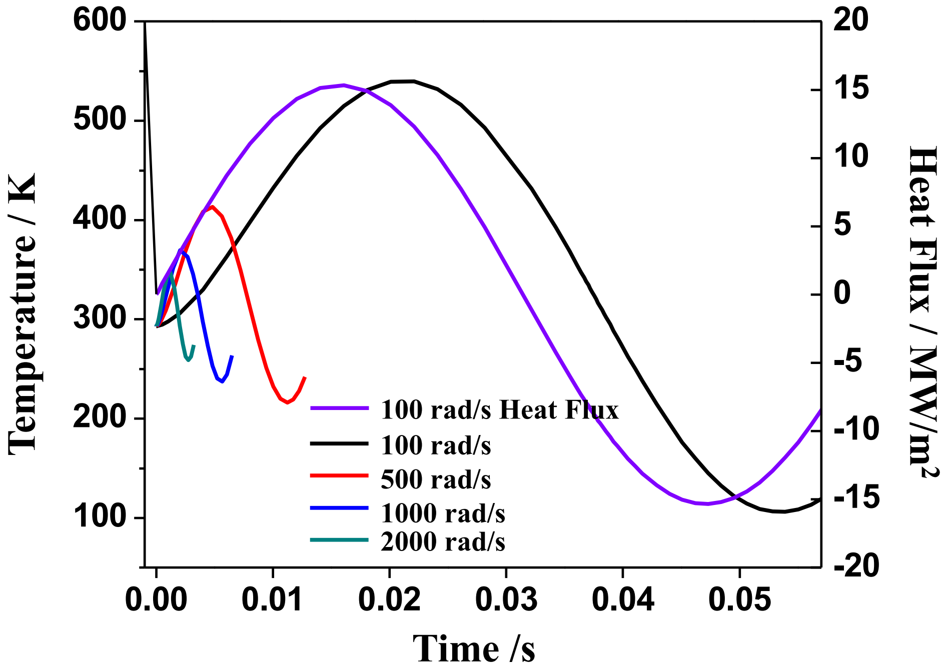
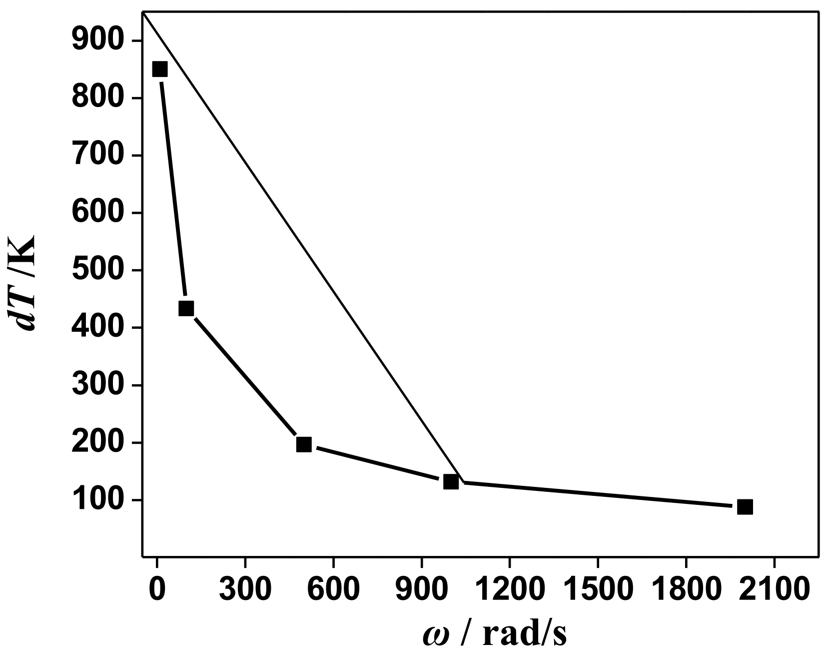


Front-side temperature oscillation over time at different frequency



Peak-to-Peak temperature at the front side as a function of angular frequency